

WORLD-CLASS OUTSTANDING INTERNATIONAL
PROGRAM | EXHIBITION | NETWORKING

HISTORY OF GEAR FAILURES IN A STEAM TURBINE DRIVEN INTEGRALLY GEARED COMPRESSOR

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29th Pump SYMPOSIA

AIR
PRODUCTS 

TEXAS A&M ENGINEERING
TEES
TURBOMACHINERY
LABORATORY



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9.30 – 10.3.2013

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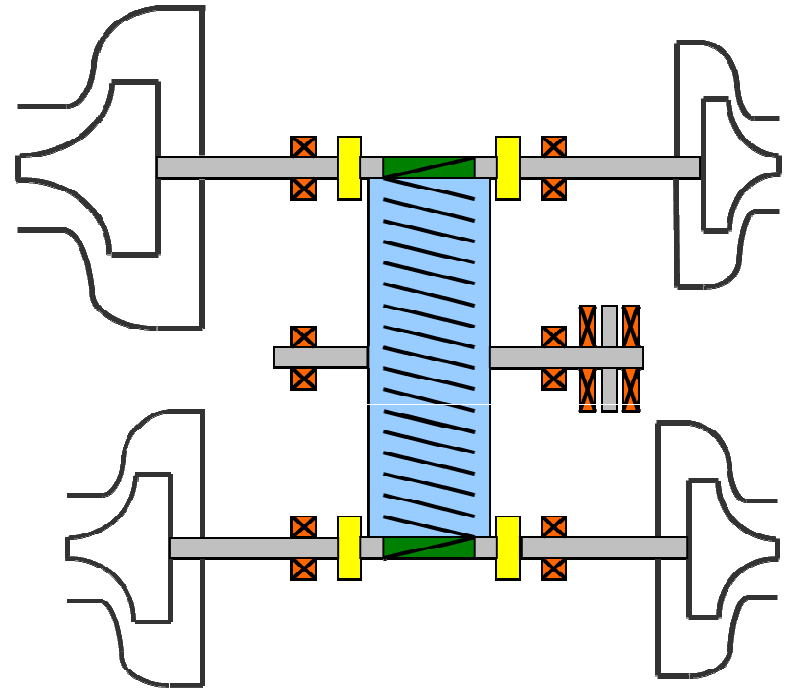


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Machine Train Configuration

- 6 stage integrally geared compressor used for compressing nitrogen to 129 bar_g
- Driven by a 16.5 MW condensing steam turbine
- Commissioned in December 2007



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Problem Statement

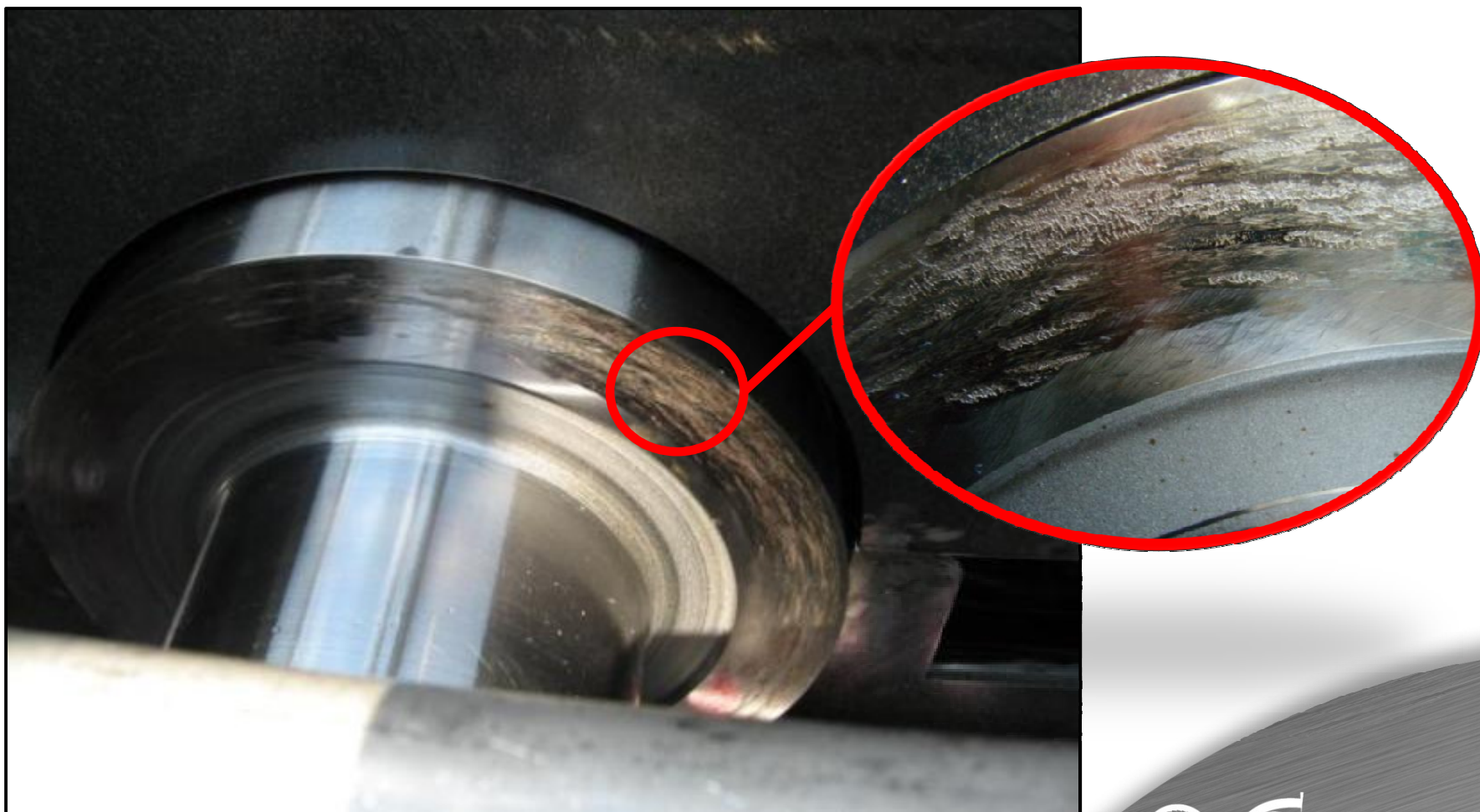
- Shutdown for routine inspection in May 2008. Found unusual wear on pinion thrust collars.
- Shutdown for routine inspection in December 2011. Found pitting on #1 pinion gear teeth.
- Machine shutdown on high vibration in October 2012. Found broken bullgear tooth and failed oil pump gearing.



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Thrust Collar Wear



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Thrust Collar Wear

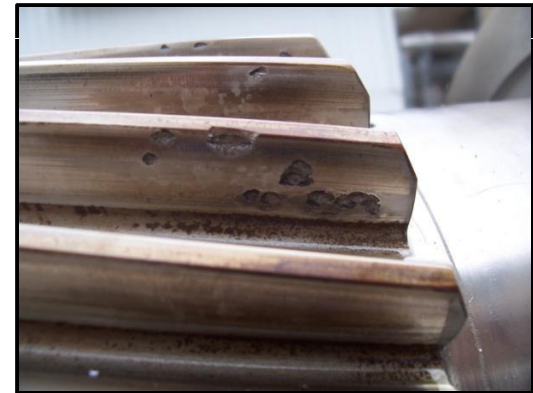
- Found in routine gear inspection in May 2008.
- Determined wear was caused by insufficient oil pressure on emergency shutdowns when the AOP was delayed in starting.
- Significant thrust collar loading on an uncontrolled shutdown
- Corrective action was to address issues with the back-up generator and to institute routine gear inspections to monitor any progression of the damage.
- Thrust collars have been inspected several times since May 2008 with no change in the surface damage.



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#1 Pinion Gear Teeth Pitting



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#1 Pinion Investigation

- Large macropits on multiple teeth, no clear damage pattern.
- Gray staining on teeth adjacent to pitting damage.
- Some pits appeared to initiate sub-surface and had a fish eye type appearance which is indicative of hydrogen contamination.
- Tested chemical and mechanical properties were acceptable.
- Oil analysis revealed that the oil additives were being depleted.
- Original oil contained zinc as part of additive package which was not recommended by the gear manufacturer.
- Gearing was highly loaded.
- Pinion was end loaded.



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#1 Pinion Failure Analysis

- Visual, metallurgical, and engineering analyses indicated that there were (3) possible root causes:
 1. Hydrogen contamination
 2. Overload
 3. Lubricant failure

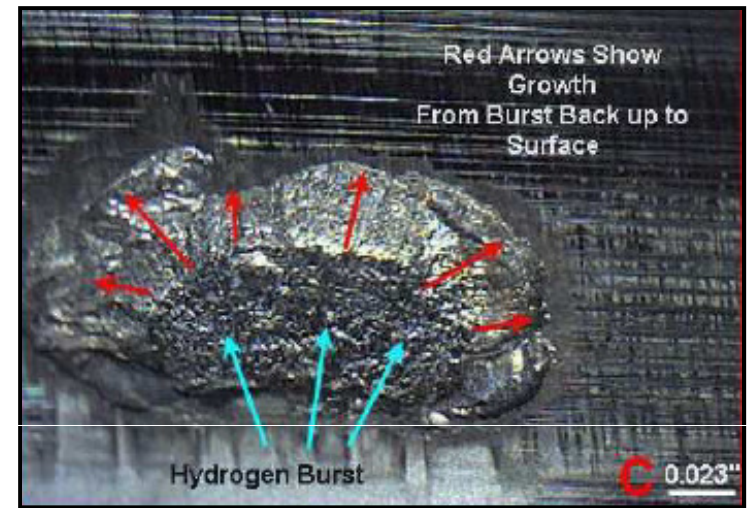


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#1 Pinion – H₂ Contamination

- Several pits had a fish eye appearance which is indicative of excessive H₂ that was trapped in the material.
- Damage initiated below the surface at internal bursts. Semi-circular, shiny in the center and rough along the edges.
- Material testing did not find excessive trapped hydrogen (<1.5 ppm).
- Corrective action:
 - Control H₂ to 2 ppm maximum.
 - Perform hot top testing during steel processing of new gear.



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#1 Pinion - Overload

- Gears specified to AGMA or DIN 3990 standards with appropriate pitting resistance and bending strength service factors.
- API-613 not required but used as a reference during investigation.



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#1 Pinion - Gear Design Parameters

PARAMETER	BULLGEAR	PINION 1	PINION 2	PINION 3	PINION 4
RATED POWER (kw)	16,420	5211	7145	4064	16,420
SPEED (rpm)	2049.5	18051	16762	20406	8234
GEAR RATIO	*	8.81	8.18	9.96	4.02
PITCH DIAMETER (mm)	1535.1	174.29	187.7	154.19	382.26
NET FACE WIDTH (mm)	210	90	90	90	210
TEETH FINISHED BY	Grinding	Grinding	Grinding	Grinding	Grinding
HARDENING METHOD	Carburizing	Carburizing	Carburizing	Carburizing	Carburizing
HELIX ANGLE	13.5				
PITCH LINE VELOCITY	164.7 m/sec				
AXIAL MESHING VELOCITY	686.2 m/sec				
MODULE	6.5				



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AGMA 2101 Requirements

- Tooth Loading

In terms of this standard the allowable unit load is defined as:

$$U_{ay} = \frac{Y_J}{\cos \beta K_O K_V K_S K_H K_B} \frac{\sigma_{FP} Y_N}{Y_\theta Y_Z S_F} \quad (16)$$

where

U_{ay} is allowable unit load for bending strength, N/mm².

- Pitting Resistance

In terms of this standard, the allowable K factor is defined as:

$$K_{az} = \frac{Z_I}{K_O K_V K_S K_H Z_R C_G} \left(\frac{\sigma_{HP}}{Z_E S_H} \frac{Z_N Z_W}{Y_\theta Y_Z} \right)^2 \quad (9)$$

K_{az} is allowable contact load factor, N/mm².



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API-613 Requirements

- Tooth Loading
- $K = [W_t / d * F_w] [R + 1/R]$
 - K is the tooth pitting index
 - W_t is the transmitted tangential load
 - F_w is the face width
 - d is the pinion pitch diameter
 - R is the gear ratio
- $K_a = I_m / (SF)$
 - K_a is the allowable K factor
 - I_m is the material index
 - SF is the gear service factor
- Pitting Resistance
- $S = [W_t / (m_n F_w)] (SF) [(1.8 \cos \gamma) / J]$
 - S is the bending stress number
 - m_n is the module number
 - γ is the helix angle
 - J is the geometry factor
- S_a is the allowable bending stress number



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#1 Pinion – Overload Results

PARAMETER	BULLGEAR	PINION 1	PINION 2	PINION 3	PINION 4
K, Tooth Pitting Index	2.9	2.2	2.9	2.0	1.6
Ka, Allowable K Factor	1.9	1.9	1.9	1.9	1.9
S, Bending Stress Number	311	258	353	201	348
Sa, Allowable Bending Stress	266	266	266	266	266

- API-613 pitting index exceeded for all pinions except pinion 4.
- API-613 bending strength exceeded for bullgear and pinion 2.
- Corrective action:
 - Confirm controls are in place to prevent overloading.
 - Ensure gear contact is centered during loaded operation.

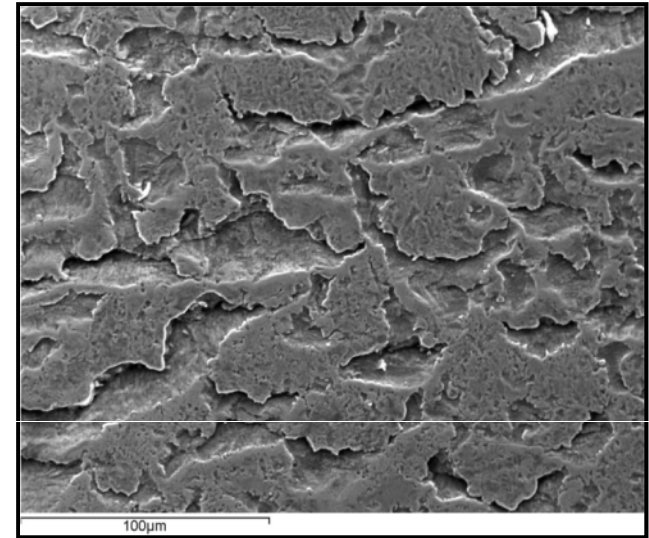


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#1 Pinion - Lubricant Failure

- Key oil requirements:
 - ISO VG32 / FZG ≥ 8.0
 - No zinc in additive package
- Actual oil:
 - ISO VG32 / FZG = 8.0
 - Contains zinc in additive package
- Gray staining appears to be micropitting which is strongly influenced by the chemical composition of the lubricant.
- Oil analysis indicates oil is breaking down
- Correction Action:
 - Investigating a lubricant upgrade
 - Upgrading oil analysis requirements



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Broken Bullgear Tooth

- Small pit observed on bullgear tooth in January 2012. Pit was dressed out; NDT did not reveal any crack indications
- Oil pump gearing failed in late October 2012. Compressor shutdown on high vibration.
- Broken bullgear tooth observed.
- Tooth was dressed out and NDT did not reveal any crack indications. Compressor was restarted. New bullgear placed on order.
- Inspected in January 2013 no progressive damage observed.



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Broken Bullgear Tooth

- Bullgear teeth show evidence of gray staining which is indicative of micropitting.
- Likely caused by same mechanism that caused macropitting damage in #1 pinion.
- Metallurgical analysis planned for bullgear after it is replaced
- No additional corrective action other than what is already planned



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Conclusions

- Gear tooth damage was likely a result of several factors – high loading without a lot of margin, end loading of pinion gear, and a lubricant failure.
- Compressor mechanical loads and complexity are on the rise and past protection strategies may not be appropriate for new machines.
- Gear damage can occur long before a failure and even moderate damage can be difficult to detect with shaft vibration probes and bearing temperature probes.
- For new compressors it is important to understand the mechanical design limits to ensure that the controls, mechanical protection limits, maintenance strategies, and spare parts strategies are appropriate for the expected reliability and availability.



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